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HYBRID COMMAND ISSUING IN A 2-DOF SERVOMECHANISM OPERATED UNDER VISION-BASED FEEDBACK CONTROL

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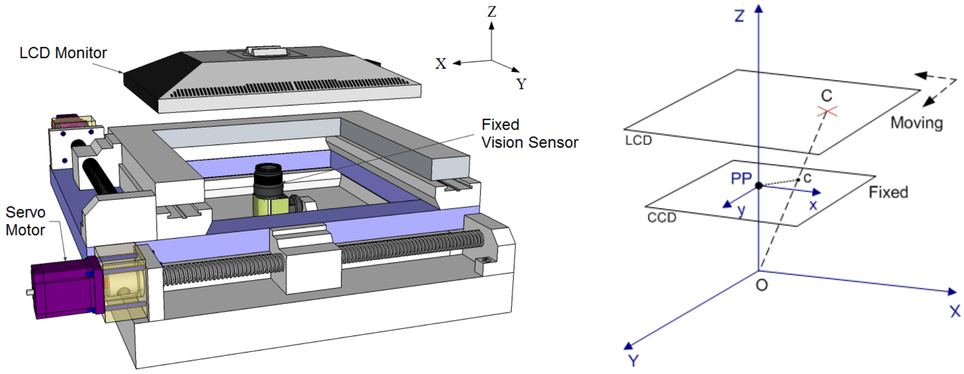
This paper presents a new method for generating motion commands in a 2 degree-of-freedom (DOF) vision-based position control system. The control system uses a fixed digital camera to direct-observe the multi-dimensional position of a known target displayed on an Liquid Cristal Display (LCD) and determines the position of the tool based on this information. This system, implemented on an XY-stage, was first introduced in Wong *et al.*, 2008, and further investigated in Montes & Ziegert, 2010 and Montes *et al.*, 2010. Previous results demonstrated sensor resolutions on the order of 3 µm; however the resolution of motion commands was constrained to values on the order of hundreds of microns due to the physical characteristics of the LCD picture elements (or pixels). The new method presented here overcomes this constraint and allows generation of motion commands as small as 3 µm. Simulation results are provided.

1 Introduction

The development of cleaner and more efficient technologies in the automotive industry has come to increase quality levels in the manufacturing sector. One of the biggest challenges in the development of new machine tools is the one related to error mapping. Common servomechanisms found in computer numerical control (CNC) machines utilize complex kinematic models of the machine to compensate errors affecting machine tool accuracy. In this work a 2 degree-of-freedom (DOF) vision-based position control system for machine tools is studied. This system is implemented on an XY-stage as shown in Figure 1 (a). A fixed vision sensor is located so that camera plane is parallel to the LCD, which moves freely in the XY plane based upon control action. In-plane motion instructions for the XY-stage are given by moving or modulating the dynamic target on the LCD, and thereby creating a position error between the target and the principal point (PP) in the camera plane (Figure 1 (b)). Initially the control system can be thought of as a tracking device, where the control system moves the machine axes to align the target on screen with PP in the image plane. However, displacements of the target on the screen are constrained by the size of the smallest element on the LCD, i.e. are constrained by one LCD pixel. The LCD pixel size in the experimental setup is 294x294 µm, i.e. motion commands are constrained to 294 µm along the LCD *Y*-axis and 98 µm (294/3) along the LCD *X*-axis. The difference between the size of *Y*-axis and *X*-axis displacements is due to the construction of one LCD pixels, which is made of three different color stripes, R, G and B, arranged horizontally from left to right. The possibility of individually generating blue, green or red from a single pixel, implies control of the physical location of the target to within 1/3 of a pixel along the LCD *X*-axis. A new method for generating displacement commands as small as 3 µm is presented next. The method, Hybrid Command Generation Protocol, combines visual-tracking and regular servo control, where the former implies the tracking of the target on the LCD and the latter implies a non-fixed reference signal to the control loop.



(a) (b)

Figure 1. (a) 2-axis stage with LCD monitor and fixed CCD camera. (b) Multi-dimensional position control error calculated based on the mapping of the target position on the LCD (point C) onto the image plane (point c) and referenced to the CCD principal point, PP.

Given the fact that the dynamics of the two axes are decoupled, it is possible to represent the experimental multiple-input multiple-output (MIMO) system as two single-input single-output (SISO) servo-systems of the form $X(s) = G(s)V(s)$, where X is the displacement along one of the axis, V is the input voltage to the servo motor and G is the transfer function. The analysis that follows is conducted for one axis (*X*-axis), only. Modeling and other considerations for the second axis (*Y*-axis) can be obtained in a similar way as for the first one.

2 Hybrid Command Generation Protocol

Due to slow hardware frame rate and long image processing times, the feedback signal from the camera is delayed in time and intermittent with respect to the controller's update frequency, affecting overall performance and stability. These factors are addressed through a model-based Smith predictor scheme, which relies on a mathematical model of the servo motors to predict the output of the plant between vision feedback-updates, only. Figure 2 shows the augmented control structure operating as a function of the discrete variable *i*, where $\hat{V}$ is used to model the intermittency and delay associated with the real camera dynamics, V, and C represents the controller. x_i^{Target} is the last increment of the target position on the LCD, with

$x_0^{Target} = 0$; x_i is the position of the stage. Commands equal to a multiple of one LCD pixel (or 1/3 of a pixel for the case of horizontal displacement commands) are issued by moving the target on the LCD by that specific distance, and setting the reference on the image plane as the origin (i.e. PP). In this case the control system operates as a regular tracking system. For commands smaller than one LCD pixel, the target is displaced by the smallest possible amount on the LCD and the reference signal is set to a value different than PP. Full attention is now paid to issuing commands smaller than one LCD pixel and introducing the necessary adaptations to make the estimate value $\hat{x}_i$ behave as $\bar{x}_i$ in Figure 2.

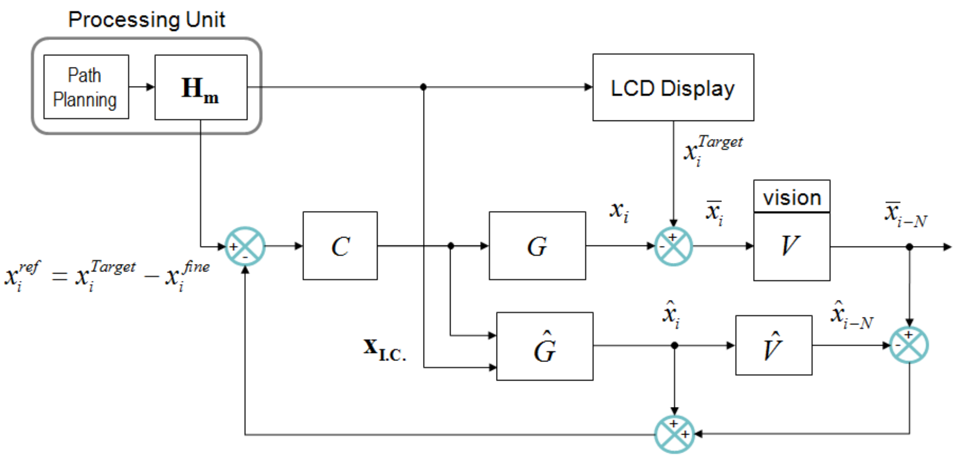


Figure 2. Single-axis command issuing through hybrid command generation protocol.

Ignoring the Smith predictor, the controller and the effects of the camera dynamics, the visual servo loop from Figure 2, can be represented by either one of the diagrams in Figure 3. The value x^{fine} is the desired displacement command, where $|x^{fine}| < 1$ LCD pixel.

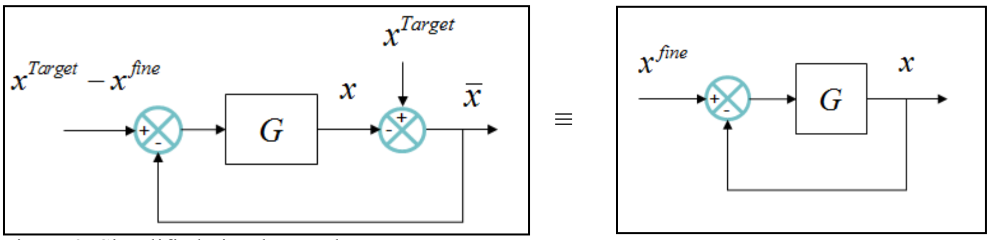


Figure 3. Simplified visual servo loop.

The closed-loop transfer function for the right-hand side diagram in Figure 3 is known to be of the form

$$\frac{X(s)}{X^{fine}(s)} = \frac{b_0}{s^2 + a_1 s + b_0} \tag{1}$$

with $b_0, a_1 \in$ ~. The differential equation associated with (1) is $\ddot{x}(t) + a_1\dot{x}(t) + b_0 x(t) = b_0 x^{fine}(t)$ with $\dot{x}(t) = dx/dt$, $\ddot{x}(t) = d^2x/dt^2$. The general solution is $x(t) = C_0 e^{r_1 t} + C_1 e^{r_2 t} + x^{fine}$ with $C_0, C_1, r_1, r_2 \in$ ~, $r_1, r_2 \le 0$, $r_1 \ne r_2$, assuming a stable non-oscillatory system. Given the initial conditions $x(0) = 0, \dot{x}(0) = 0$, it follows that $C_0 = \left(r_2 / r_1 - r_2\right) x^{fine}$ and $C_1 = \left(r_1 / r_2 - r_1\right) x^{fine}$. Hence,

$$x(t) = x^{fine}\left(\frac{r_2}{r_1 - r_2} e^{r_1 t} + \frac{r_1}{r_2 - r_1} e^{r_2 t} + 1\right) \tag{2}$$

Equation (2) indicates that the position of the stage along the *X*-axis converges exponentially to x^{fine}, as desired. From the left-hand side diagram in Figure 3, it follows that

$$\overline{x}(t) = x^{Target} - x^{fine}\left(\frac{r_2}{r_1 - r_2} e^{r_1 t} + \frac{r_1}{r_2 - r_1} e^{r_2 t} + 1\right) \tag{3}$$

The value of $\overline{x}$ is now well defined for the required reference signal $x^{ref} = x^{Target} - x^{fine}$ to command the stage to move by x^{fine} µm. It is necessary at this point to determine the conditions to make the model $\hat{G}$, in Figure 2, provide an appropriate estimate of $\overline{x}$. Let the differential equation associated with $\hat{G}$, for a reference signal $x^{ref} = x^{Target} - x^{fine}$, be $\hat{x}(t) = \hat{C}_0 e^{\hat{r}_1 t} + \hat{C}_1 e^{\hat{r}_2 t} + \left(x^{Target} - x^{fine}\right)$ with $\hat{C}_0, \hat{C}_1, \hat{r}_1, \hat{r}_2 \in$ ~, $\hat{r}_1, \hat{r}_2 \le 0$, $\hat{r}_1 \ne \hat{r}_2$ and $\|r_1 - \hat{r}_1\|^2 < B1$, $\|r_2 - \hat{r}_2\|^2 < B2$, $B1, B2 \in$. For initial conditions $\hat{x}(0) = x^{Target}$, $\dot{\hat{x}}(0) = 0$ it is possible to calculate $\hat{C}_0 = -\left(\hat{r}_2 / \hat{r}_1 - \hat{r}_2\right) x^{fine}$ and $\hat{C}_1 = -\left(\hat{r}_1 / \hat{r}_2 - \hat{r}_1\right) x^{fine}$, and the solution to the model becomes

$$\hat{x}(t) = x^{Target} - x^{fine}\left(\frac{\hat{r}_2}{\hat{r}_1 - \hat{r}_2} e^{\hat{r}_1 t} + \frac{\hat{r}_1}{\hat{r}_2 - \hat{r}_1} e^{\hat{r}_2 t} + 1\right) \tag{4}$$

A direct comparison between (3) and (4) demonstrates that, if the initial conditions of the model $\hat{G}$ are updated according to the latest position of the target as imaged by the camera, x^{Target}, then $\hat{x}(t)$ is indeed an estimate of $\overline{x}(t)$. It is worth pointing out that

x^{Target} is known at all times. $\mathbf{H_m}$ in Figure 2 is used to calculate the required vectors $\mathbf{x^{Target}}$ and $\mathbf{x^{fine}}$, according to a predefined path plan. The input vector $\mathbf{x_{I.C.}} = \left[x(0) \quad \dot{x}(0) \right]^{T}$ illustrates the initialization of the model states according to $\mathbf{x^{Target}}$.

3 Simulation Results

A basic path plan for fine in-plane displacement is generated. Figure 4 shows the desired motion for each axis in (a) and (c) (continuous traces), as well as the required target position on the LCD (discrete traces). The required reference signals to the control system according to the path plan are shown in (b) and (d).

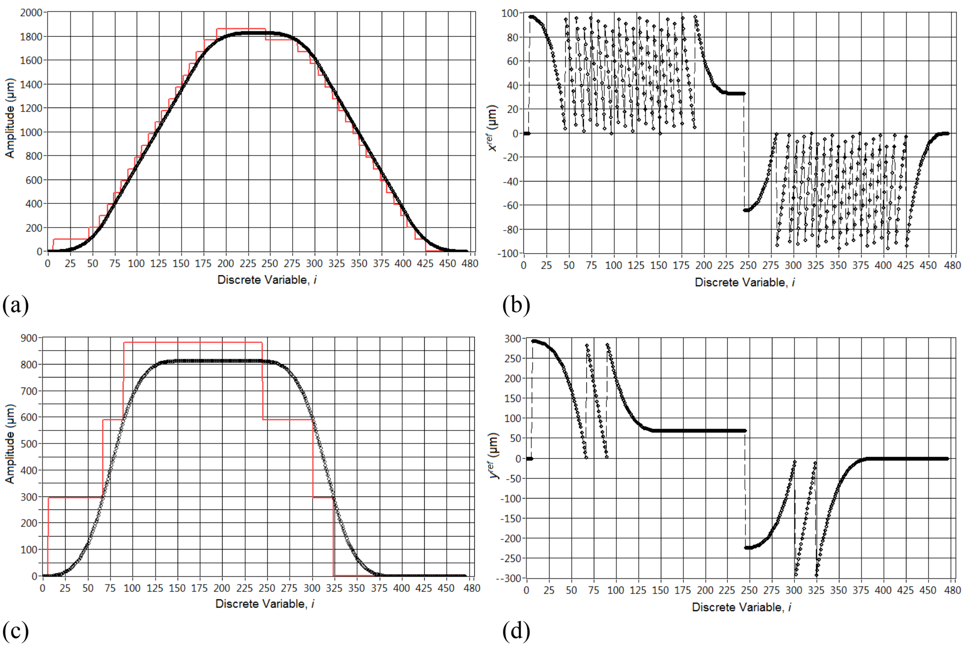


Figure 4. (a) *X*-axis path plan (continuous trace) and corresponding (required) target position on LCD (discrete trace). (b) *X*-axis reference control-signal required for path plan. (c) *Y*-axis path plan (continuous trace) and corresponding (required) target position on LCD (discrete trace). (d) *Y*-axis reference control-signal required for path plan.

Simulation is conducted by feeding the path plan in Figure 4 to the control system in Figure 2. The results are shown in Figure 5 for a controller frequency of 1 kHz and a vision block capable of providing feedback data at 400 Hz. The frequency for the vision block is defined based on image acquisition times and image processing times obtained from previous experiments. The graph in (a) shows that it is possible to obtain an output motion that is close to the desired path through small controller gains. However, the velocity pattern in (b) presents undesired oscillations. These oscillations are associated with wait times that the control loop has to undergo in between feedback updates from the vision sensor. These oscillations can be addressed by increasing the rate at which the image is displaced on the LCD, or by adding a feed forward compensator to reduce the velocity of the control system.

(a)

(b)

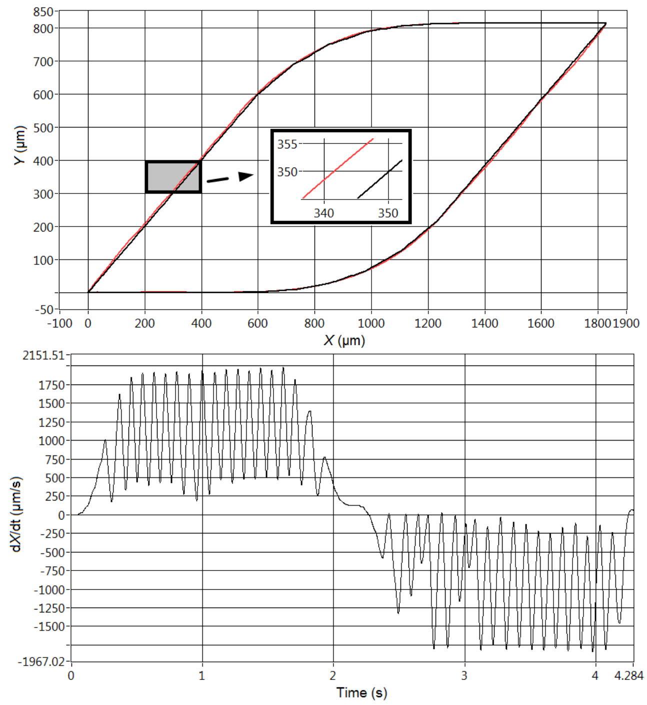


Figure 5. Simulation results with a 1 kHz proportional controller and a vision block capable of providing feedback signals at 400 Hz. Proportional gains: P_x=30; P_y=30. (a) Desired in-plane motion and simulation output plotted on same graph. Highlighted rectangular-area shows biggest deviation between desired and simulated motion. (b) Output velocity, *X*-axis.

4 Conclusion

A method for generating motion commands as small as 3 µm for a pre-existing real time control system was presented. Simulation results indicated a need for a velocity compensator to achieve desired motion behavior.

Acknowledgements

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